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PREFACE

The North Atlantic Treaty Organization (NATO) has sponsored research and personnel safety standards development for exposure to Radiofrequency Radiation (RFR) for over twenty years. The Aerospace Medical Panel of the Advisory Group For Aerospace Research and Development (AGARD) sponsored Lecture Series No. 78 *Radiation Hazards*,[1] in 1975, in the Netherlands, Germany, and Norway, on the subject of Radiation Hazards to provide a review and critical analysis of the available information and concepts. In the same year, Research Study Group 2 on Protection of Personnel Against Non-Ionizing Electromagnetic Radiation (Panel VIII of AC/243 Defence Research Group, NATO) proposed a revision to Standardization Agreement (STANAG) 2345. The intent of the proposal was to revise the STANAG to incorporate frequency-dependent-RFR safety guidelines. These changes are documented in the NATO STANAG 2345 (MED), *Control and Recording of Personnel Exposure to Radiofrequency Radiation*,[2] promulgated in 1979.

Research Study Group 2 (RSG2) of NATO Defense Research Group Panel VIII (AC/243) was organized, in 1981, to study and contribute technical information concerning the protection of military personnel from the effects of radiofrequency electromagnetic radiation. A workshop at the Royal Air Force Institute of Aviation Medicine, Royal Aircraft Establishment, Farnborough, U.K. was held to develop and/or compile sufficient knowledge on the long-term effects of pulsed RFR to maintain safe procedures and to minimize unnecessary operational constraints. That workshop brought together eighteen scientists from six NATO countries and resulted in Aeromedical Review 3-81; *A Workshop On The Protection Of Personnel Against Radiofrequency Electromagnetic Radiation*.[3] Also in 1981, a NATO Advanced Studies Institute (ASI) on *Advances in Biological Effects and Dosimetry of Low Energy Electromagnetic Fields* was held in Erice, Sicily, Italy (Also the fourth course of the International School of Radiation Damage and Protection of the Ettore Majorana Center for Scientific Culture). This meeting resulted in an ASI publication; *Biological Effects and Dosimetry of Non-ionizing Radiation: Radiofrequency and Microwave Energies*.[4]

In 1984, the Research Study Group Panel VIII NATO AC/243, held another workshop in Wachtberg-Werthoven, Federal Republic of Germany with over 40 scientists from five NATO countries attending. The consensus of the participants was that the workshop provided a significant and effective update on the state-of-knowledge regarding the biological effects of RFR and current developments in the setting of new RFR safety standards. The proceedings of the second workshop were published as USAFSAM-TP-85-14: *Proceedings Of A Workshop On Radiofrequency Radiation Bioeffects*.[5] That same year, a NATO Advanced Research Workshop (ARW) examined the *Interaction Between Electromagnetic Fields and Cells*,[6] in Ettore Majorana Center for Scientific Culture, Erice, Sicily, Italy. The 1984 workshop concluded that "It is important that today's RFR bioeffects research results, emerging from many countries, continue to be disseminated as efficiently as possible for consideration and use by the NATO military organization." The theme of the most recent AGARD lecture series, presented in Italy, Portugal, and France in 1985 was *The Impact Of Proposed Radiofrequency Standards On Military Operations*.[7]

EVALUATION OF ELECTROMAGNETIC FIELDS IN BIOLOGY AND MEDICINE

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INTRODUCTION

While influences of electricity and electromagnetic fields on biological systems were observed as early as the 18th century (Galvani) and the 19th century (d'Arsonval), and numerous speculations have been advanced since, a rigorous inquiry started after the Second World War. By the mid-seventies a broad range of topics was addressed, including potential health hazards of human exposure to electromagnetic energy. The interest in this field has been to a large extent stimulated by the worker and public concerns and pressures regarding safety of proliferating technologies. The main effort has concentrated in two frequency ranges: power line frequencies (50-60 Hz), and radiofrequencies (RF) and microwaves (from a few kHz to hundreds of GHz).

Considerable progress has been made in understanding the interactions of RF and microwave fields with living systems. This understanding and agreement among the majority of scientists and regulators have resulted in very similar or nearly the same recommendations regarding safe exposure levels in many national standards and international guidelines.

Despite a lot of effort, particularly in the last decade, the mechanisms of interaction of extremely low frequency (ELF) electric and magnetic fields of relatively low intensities remain poorly, if at all, understood. Similarly, there is no convincing evidence if, at what level and under what conditions can these fields be harmful to human health. The following brief overview is aimed at evaluating the state of knowledge regarding electromagnetic fields in biology and medicine. A comprehensive review of health effects and medical application is not attempted; instead reference to current reviews are given. Critical unresolved issues are emphasized.

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RF AND MICROWAVE (MW) FIELDS

Far-field Exposures - Bioeffects

Biological effects of RF/MW fields have been extensively investigated as documented in several reviews.[1-4] With the help of dosimetric modeling, thresholds of the average specific absorption rate (SAR) have been established for various effect, in animals. Some examples follow. Radiofrequency radiation is teratogenic at SARs that approach lethal levels, and a threshold for induction of birth defects is associated with the maternal core temperature of 41-42°C. Chronic exposure of rats during gestation at 2.5 W/kg was reported to result in lowered fetal body weight at weaning. Temporary sterility in male rats occurred at an SAR of 5.6 W/kg, which produced a core temperature of 41°C. Decreases in operant- and learned-behavioral responses occur at SAR = 2.5 W/kg in the rat and at 5.0 W/kg in the rhesus monkey. Some types of behavior are affected at SARs approximately 25 - 50% of the resting metabolic rate. These behavioral changes are reversible, with time, after exposure ceases. Changes in the endocrine system and blood chemistry at SARs greater than 1 W/kg and in hematologic and immunologic systems at SARs equal and greater than 0.5 W/kg, for prolonged exposures, appear to be associated with thermal stress. One group of researchers reported that chronic exposure at SARs of 2-3 W/kg resulted in cancer promotion or co-carcinogenesis in mice. The effect was similar to that caused by chronic stress. Neurons in the central nervous system were altered by chronic exposure at 2 W/kg. All these effects appear to be associated with thermal load due to RF exposure and are characterized by thresholds.

In summary, for whole-body exposures to RF/MW radiation the experimental data currently available strongly suggest that biological effects in mammals occur at average SARs of about 1 W/kg. This database is well established and consistent. This fact has been reflected in more recent exposure standards such as the U.S. ANSI/IEEE C95.1-1991, Canadian Safety Code, 1991 Revision, the U.K., NRPB Standard. Each of these documents contains reference either in the text or in the accompanying publication to the same database.[1-4]

Portable Transmitters

An evaluation of spatial distributions of SAR from RF/MW transmitters presents challenging problems both theoretically and experimentally. The main difficulties are due to geometrical complexities and biological tissue heterogeneities. Several theoretical and experimental investigations of the SAR distribution in various models of the human body have been conducted.

Apart from theoretical solutions for overly simplified geometries and electrically small antennas, the first numerical evaluation was performed by the tensor integral method.[5] The human body was modelled by 180 cubical cells of varying sizes to best fit the contour of a 70-kg man. A thin resonant dipole was located with the feed point at the neck level, 7.3 cm away from the body. Calculations were performed at 350 MHz. The results were later compared with the experimental data.[6] This model did not accurately predict local and even sub-regional SARs. Essential features of the energy deposition pattern, such as an exponential decay with the distance away from the surface of the local SARs at the plane of the antenna feed, and a "hot spot" in the neck, were not identified by this model.

Because of the serious limitations of the existing numerical techniques in the early 1980s, an experimental approach was explored.[7] A full-scale heterogeneous human model, was constructed from a 1 mm thick fiberglass shell. The following organs and tissues were

placed inside the shell: a skeleton comprised of a skull, spinal cord, rib cage, and all major bones except those in the feet and hands; brain; lungs; and muscle. The dielectric properties of all materials stimulating the tissues closely corresponded to those of the respective *in vivo* tissues at test frequencies. Resonant dipole antennas were placed in front of the model at distance of 0.06λ, 0.07λ, and 0.2λ at the three test frequencies: 160, 350 and 915 MHz, respectively. The electric field inside the model was measured using a miniature implantable electric field probe with a computer-controlled scanning and data acquisition system.[8] The main findings were that: (1) significant (an order of magnitude) differences exist in SARs between heterogeneous and homogeneous models having the same shape, (2) at all three test frequencies the maximum SAR is produced at the surface of the model (across from the feedpoint), and the SAR close to the surface of the model decreases exponentially with distance in the direction perpendicular to the surface, (3) at 160 and 350, but not at 915, MHz there is a "hot spot" in the neck, and (4) in all cases most of the energy is deposited in about 20% of the total body volume closest to the antenna feed point. It should be noted that because of the antenna position modeled, the SARs in the eye are lower than if the antenna was located closer to the eye, as is common in a normal use of portable transmitters.

Other experimental evaluations were also performed; notably, two portable transceivers were assessed, one operating in the range of 810-820 MHz with an output power of 1.8 W, and the other operating at 850-860 MHz with 1 W of output power.[9] A heterogeneous model of the head was used with simulated skull, brain, eye, and muscle tissues. The electric field in tissue was measured with an implantable probe. Similarly, as in Stuchly et al.,[7] a maximum of the electric field on the surface and decay with distance were observed. The estimated maximum SARs on the surface of the eye were 3.2 and 1.1 W/kg per 1 W of the input power for the 810-820 MHz transmitter and 850-860 MHz transmitter when the speaker was placed flush with the operator's mouth. These values decreased to 1.1 and 0.7 W/kg per 1 W when the speaker was 2.5 cm away from the mouth. Comparable SAR values were measured in the temple and forehead areas.

More recently, numerical modeling using 3-dimensional multiple multipole (MMP) method was applied to resonant-dipole antennas in the proximity of biological bodies[10,11]. The computations were verified experimentally for a planar tissue model.[12] An approximate formula for the SAR induced at the surface of a lossy semi-infinite planar tissue was derived. The peak SAR is proportional to the square of the surface incident magnetic field, and depends on the tissue electric properties and the antenna-tissue distance expressed in wavelengths. For resonant dipoles the incident magnetic field is proportional to the antenna feed-point current, and inversely proportional to the distance. These properties apply at frequencies higher than 300 MHz. It was also estimated that for a 7 W, 1.5 GHz transceiver 2.5 cm from the eye, the peak SAR would be 40 W/kg (averaged over 1 g of tissue). A conclusion reached in this work was that very close to an antenna (a small fraction of the wavelength), the SAR is not directly related to the power radiated but to the antenna current.[12]

Deposition of energy from a dipole in a heterogeneous model of human head was evaluated by finite-difference time domain method.[13] This is so far the most accurate SAR determination in the head, and especially the eye. Computations were done at 900 MHz and 1.9 GHz. These computations confirmed that higher SARs close to the surface of the eye are obtained at the higher frequency. Data are given for SARs in the eye and 1g tissue for various separations of the antenna from the head. SARs of about 3 W/kg per 1W of the power to antenna are predicted for the antenna-head separation of 3 cm at 900 MHz and at 1.9 GHz (for the higher frequency the SAR is somewhat higher).

In the case of portable transmitters, it is apparent the average SAR is not the critical parameter in terms of protection against health effects, since the power deposition (SAR) is localized in the vicinity of the antenna. In most cases that means energy deposition in the eyes and the head.

Effects of electromagnetic radiation on the three major eye components essential for vision, cornea, lens and retina, have been investigated.[1,14] The largest number of studies has been concerned with cataracts. It was established that lens opacities can form after exposure to microwaves above 800 MHz but below about 10 GHz cataract induction requires sufficiently long exposures at an incident power density exceeding 100 mW/cm^2. SARs in the lens large enough to cause temperatures in the lens greater than 41°C are required. Effects on retina have been associated with rather high levels of microwave radiation, above 50 mW/cm^2. More recently, effects of microwaves on the cornea have been investigated.[15,16] One of the essential parts of the cornea is the endothelium.[15] Its damage can lead to corneal edema and visual loss. Studies of the effects on the corneas of monkeys have indicated that 2.45 GHz radiation causes damage to the corneal endothelium.[13] Lesions were found sixteen to twenty-four hours past exposure, for exposures to 30 mW/cm^2 for CW and 10 mW/cm^2 for pulsed radiation (10ms, 100pps). The estimated SAR in the cornea was 0.26 W/kg per 1 mW/cm^2. A subsequent study of the pulsed radiation and two ophthalmic drugs revealed a lowering of the thresholds for damage.[16] The drugs used were those clinically used for treatment of glaucoma. Treatment with these drugs lowered the thresholds for microwave damage to below 1 mW/cm^2 (SAR of 0.26 W/kg).

Dosimetric data, as well as the observed biological effects on the retina, demonstrate a need for specific recommendations with respect to exposure from portable transmitters. Such recommendations have been made in the U.S.[17] and Canada[18]. However, the scientific basis behind them was relatively limited at the time they were developed.

Amplitude Modulated Fields

Biological effects have been observed at RF and MW fields amplitude modulated at ELF at SAR levels below thresholds for effects for continuous waves.[1,19,20] Many of these effects are the same or similar to effects observed for ELF electric and magnetic fields. The observed effects are usually field frequency and intensity specific, tend to occur within relatively narrow ranges of both field parameters, and are dependent on other physical and physiological characteristics of the exposed biological system. Many of these parameters have not been fully identified and characterized. The interaction mechanisms remain unknown. The scientific database is relatively limited in this area. However, the potential importance of these effects should not be overlooked for two reasons. First, the scientific evidence with respect to health effects of ELF fields while still inconclusive, is suggestive of possible detrimental effects. Second, until the recent developments in digital communication, hardly any situations of human exposure to RF/MW fields deeply amplitude modulated at ELF occurred. This situation is going to change rather rapidly with expansion of wireless digital communication.

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Medical Applications

RF/MW fields have found a few important medical applications.[19] Hyperthermia, available for some time, is becoming a recognized form of cancer therapy, particularly when used as an adjunct to other modalities such as radiotherapy and chemotherapy. Heat has been used in medical therapy since antiquity, while in this century scientific investigations have provided a better understanding of the interaction and more effective clinical application.[20] There are numerous comprehensive reviews of electromagnetically induced hyperthermia.[20-23] Frequencies used range from hundred kilohertz to a few gigahertz.

Many devices operate at the frequencies allocated for industrial, scientific, and medical (ISM) applications to avoid potential interference with communication and other electronic systems. The selection of the operating frequency as well as the type of applicator (the device that determines the spatial distribution of the electric field in the treated tissue) depend on the location and size of the malignancy. The applicator design depends on whether localized or regional hyperthermia is required and whether the tumor is superficial or deeply located. Among a variety of applicators and methods of electromagnetic tissue heating, magnetic induction has been successfully used in many experimental and clinical applications. Various applicator designs are used to produce desired patterns of induced electric fields in the treated tissue. Particularly successful have been applications of microwave energy for tissue heating or destruction through interstitial applicators.[24] In addition to treatment of various tumors, this technique has been successful in treatment of non-malignant disorders of prostate.[25,26] Other applications include angioplasty and ablation.

In Magnetic Resonance Imaging (MRI) and Magnetic Resonance Spectroscopy (MRS), the nuclear magnetic resonance is produced by a strong static magnetic field, a time-varying magnetic field, and RF pulses and is used to image body tissue and to monitor body chemistry. Both techniques have gained wide acceptance, and there are increasing ranges and volumes of applications. Since 1982, following the first publication of the image of the human body, MRI has been available clinically.[19] MRI provides comparable, and in some cases superior, detection capabilities of abnormal tissue to those of X-ray computer tomography (CT). For abnormalities in the brain, spinal cord, various abdominal regions, breast, and the cardiovascular and musculoskeletal systems, MRI appears superior to other modalities. MRS is used to diagnose metabolic disorders in selected regions of tissue. The metabolism of high-energy phosphate compounds, C-labelled metabolites, and many other endogenous or injected compounds can be evaluated[19]

In several applications, electrical energy must be transferred through intact skin. In the first group of applications, implanted medical devices require more power than can be supplied by presently available batteries over a sufficiently long period of time. The second category includes implanted devices that are passive receivers. The third category covers various biotelemetry systems, where information about physiological parameters within the body is transmitted to an external system. Transcutaneous energy and signal transmission (TET) has a great advantage since a tethering cable poses a serious medical problem as a source of infection and complications such as air leaks, tissues tearing and bleeding. In all TET applications, a pair of coils is used. The coil outside the body couples electromagnetic energy to the coil inside the body. Telemetry is probably the oldest application of TET. In this case, the function of the coils is reversed, with the internal coil acting as a transmitter. There are many applications of telemetry, e.g., monitoring intracranial pressure, pH of the digestive tract, bioelectric activity, and many others. Recently, systems have been developed to extend the lifetime of implanted biotelemeters by recharging implanted batteries using magnetic fields.[19] In all aforementioned TET devices, only a relatively small amount of power is transferred. Since the 1960s, there has been interest and considerable progress in developing TET systems to power cardiac assist devices and a total implantable heart. Some systems have been evaluated in animals and found to be able to transfer up to 100 W over a long period of time without any noticeable detrimental effects.

Medical applications of RF and MW fields have provided information relevant to both the evaluation of energy deposition, particularly from local sources, and to understanding biological interactions and thermal tolerance. As such, they are of some use in development of human exposure standards.

EXTREMELY LOW FREQUENCY (ELF) FIELDS

Biological Effects

The last decade witnessed considerable scientific effort as well as public concern regarding potentially harmful effects of human exposure to ELF and more specifically the power line frequency fields. The main concern is due to a number of epidemiological studies that have shown associations between exposure to low magnetic flux densities (of the order of 0.2 - 0.3 μT) and rates of childhood leukemia and, to a lesser extent, brain cancer. Similarly suggestive evidence between the rates of some cancers and exposures associated with so called "electrical" occupations have been provided by epidemiological studies of various cohorts of workers. Several recent reviews outline the results and evaluate the limitations of the studies.[26-29] The latter range from surrogate measures of exposure to very small numbers of cases in high-exposure groups, limiting the statistical power of the findings. While most of these studies suffer from at least some limitations, the weight of the evidence cannot be dismissed. The main problem is a limited amount of experimental data that could support the findings of the epidemiology. Some experimental results are outlined below that may at least partly support the proposition that ELF fields affect the development of cancer.

Magnetic fields were found not to cause mutagenic effects, as investigated by the Ames test and studies of chromosome aberrations and sister-chromatid exchanges in human peripheral blood. There was no significant difference in DNA single-strand breaks in mammalian cells exposed to magnetic fields. DNA repair mechanism was also not affected by pulsed magnetic fields of 2.5 mT (peak) and 1 T/s.[19,27]

A few studies of carcinogenicity have been done on animals. Large scale studies are now underway. Cancer development is considered in experimental models as a multistage process involving initiation (a change in the cell genetic material - DNA), promotion and progression. Promotion is associated with repeated exposures to an agent that may also act as an initiator (e.g., X-rays) or only as a promoter (many chemicals). Promotion involves interactions at the cell membranes. Progression is the last stage involving rapid growth of tumor and metastasis. Since electromagnetic fields have not been found to cause genetic changes, most investigations have been concentrating on promotion and co-promotion. As co-promotion one considers modification either through an accelerated rate of development or a greater incidence of cancer produced by two chemical agents, both an initiator and a promoter. Three studies, two in Sweden and one in Canada, have shown that magnetic fields do not act as promoters. The Canadian study has shown that a relatively strong magnetic field accelerated the rate of development of tumors in mice, but not the final yield in terms of the number of tumors and the number of animals affected. One Swedish study did not show any co-promoting effect, and the other showed a slight inhibition of the rate of tumor growth. So while here appears to be some biological interaction, at least in some cases, the actual effect magnetic fields have, if any, in cancer development remains undetermined.

There has been a plethora of laboratory investigations of various isolated cells in culture. These studies have clearly shown that electromagnetic fields of low frequencies can interact with biological systems at moderately low and some times very low intensities. Typical responses reported were altered cell growth rate; decreased rate of cellular respiration; altered metabolism of carbohydates; proteins and nucleic acids; changes in gene expression and genetic regulation of cell function; and altered hormonal responses. Recently, further observations were reported regarding effects on cellular transcription, charge on the cell surface, ATP and oxygen levels in the slime mold, growth, proliferation, and functional differentiation of cells.[19,27] Several studies have reported changes in calcium efflux.[19,27]

Another important effect of ELF fields is suppression of melatonin production and alterations in circadian rhythms. Effects on melatonin have been shown both in-vitro and in animals.

The main problem in evaluating of biological effects of ELF fields is the complexity of observed interactions. Effects observed are not always proportional to the field strength or the magnitude of induced currents. Sometimes, they show "window" responses in the field frequency and amplitude, and cell physiological state. The critical parameters responsible for the effect are often not well defined nor are they understood. This makes the reproduction of these experiments in different laboratories difficult, and sorting out what is a real effect and what may well be an experimental artifact is quite challenging. Difficult as these experiments are, they are extremely important in elucidating how the interactions occur, and what are the physical, biophysical and biological mechanisms of action.

Medical Applications

Since the mid-1960s, when effects of electric currents on bone growth were described,[30] there have been many successful clinical applications of ELF currents to reverse therapeutically pathologic processes in the musculoskeletal system, among them healing of non-unions. Non-union is the failure of a bone to heal normally following a fracture. In non-united fractures, the induced currents trigger calcification of the gap tissue and result in boney union. Successful applications are in the treatment of non-united fractures, infantile non-unions, and arthrodesis. To develop further clinical applications of pulsed magnetic fields for growth and repair of various tissues, several experimental studies in animals have been conducted including ligament and tendon repair, soft-tissue wound healing, osteoporosis, nerve regeneration, and liver regeneration. Pulsed magnetic fields were found promising in lowering the serum glucose levels in diabetic rats. Unfortunately, a large number relatively poorly conducted studies here contributed little to the understanding of important therapeutic applications.

Investigations of medical applications of ELF fields and their mechanisms of action are closely related to the study of these fields from the point of view of prevention of harm.

CONCLUSIONS

Electromagnetic fields can interact with biological systems and under some conditions affect human health. Some of these interactions can be harmful, while others can be beneficially employed in medical diagnosis and therapy. A lot has been learned about the interaction mechanisms and biological effects of RF and MW radiation. However, mechanisms of interaction and the range of biological effects of ELF fields remain enigmatic despite an increased research effort in the last decade.

For RF/MW exposures in the far-field, interactions are well quantifiable in terms of average SARs with some additional allowances for local SARs. The existing database provides sufficient information to establish protection standards. In view of the relative coherence of recent exposure standards in various countries, it appears reasonable for STANAG to derive its recommendations directly from one of the recent standards, e.g., the U.S. IEEE/ANSI (1991) recommendations.

The situation is more complex for portable and perhaps mobile transmitters. For analog devices (no ELF amplitude modulation), the IEEE/ANSI, 1991 recommendations provide a good starting point. However, the more recent dosimetry data and biological data on ocular effects should be evaluated and incorporated. Because of a much greater variety of portable/mobile devices and their higher power in military applications than in civilian applications there is a need for careful evaluation. Since modeling techniques and computer capabilities have significantly progressed in the last few years and the existing database is limited, more dosimetric evaluations should be undertaken. Also, the ocular effects have to be confirmed in another laboratory and further evaluated.

The resolution of potentially harmful effects of ELF fields and conditions under which they occur requires still a lot of scientific effort; only some of it is underway. It would be premature to set up an exposure standard at this time. If the standard were based on well established and understood tissue stimulation thresholds, as e.g.,[31] it would not reflect the current scientific database indicating biological interactions, some of which may prove harmful at much lower field levels. On the other hand, the weak field effects are still so poorly understood and not quantifiable that the existing scientific evidence is not suitable for standard setting. There is an urgency to understand these interactions and find out whether and at what levels effects of ELF fields also occur at RF/MW field amplitude modulated at ELF. Little research is being conducted in this area at present, but in view of the important role played by wireless digital communication, this area deserves attention.

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Building Penetration Loss Measurements at 900 MHz, 11.4 GHz, and 28.8 GHz

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May 1994

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conversation
with N.D.

Attenuation

$$= -10 \log \left(\frac{\text{Power outside}}{\text{Power inside}}\right)$$

Ex:

$$-6\,dB = -10 \log (R)$$

$$.6 = \log R$$

$R = 4$ power outside
is 4 x as strong
as inside

at high frequencies measure
strength using power density
not volts.

CONTENTS

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

FIGURES (Cont'd)

FIGURES (Cont'd)

TABLES

BUILDING PENETRATION LOSS MEASUREMENTS AT 900 MHZ, 11.4 GHZ, AND 28.8 GHZ

K. C. Allen, N. DeMinco, J. R. Hoffman, Y. Lo, and P. B. Papazian*

The feasibility of using radio frequencies in the super high frequency (SHF) band (3-30 GHz) for Personal Communications Services (PCS) in buildings depends on the multipath within the structure and the amount of attenuation experienced by the electromagnetic waves passing through the structures. This study measured these effects to obtain a quantitative estimate of the attenuation magnitude. This magnitude can then be used for link margin analysis to determine if personal communications at SHF is practical.

keywords: building attenuation, measurements, PCS, penetration attenuation, personal communications

1. INTRODUCTION

This report describes the results of a measurement program. The objective was to determine if frequencies in the super high frequency (SHF) band (3-30 GHz) can be used for Personal Communications Services (PCS) between the outside and inside of buildings in a manner like that currently used for cellular telephone at 900 MHz. The crowding of the radio frequency spectrum at 900 MHz makes it probable that PCS will be required to operate at the higher frequency bands. PCS is a class of telecommunications services that includes a wide range of capabilities, such as telephony, data transfer, paging, voice mail, and electronic messaging. PCS will provide portability and personalized telephone service to users. Many small cells similar to the cells used in cellular phone systems can be used to provide low-cost communication services through pocket-size, low-power, portable telephones to individuals wherever they may be in the service area.

The Institute for Telecommunication Sciences (ITS) has been active in the development of computer models and measurements to assess system losses in typical PCS operational environments for the proposed frequency bands. Models are being developed for urban outdoor microcells and within-building environments. The building penetration measurements described in this report will provide some insight into the degree of attenuation experienced by PCS signals when penetrating three typical structures.

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The experimental results in this report have been obtained to help determine the excess path loss associated with reception inside buildings and its dependence on location within the building and the building type. The data contained herein will also help to quantify the spatial variation of signal due to severe multipath.

The constructive and destructive interference at SHF frequencies are expected to vary over a much smaller spatial separation than would occur at lower frequencies and hence provide a means of obtaining space diversity reception over a short distance comparable to the size of the personal communicator set. Over a narrow bandwidth, this should minimize signal fading variations due to multipath and provide good communication performance for such a system.

This report describes the results of signal strength measurements made inside three types of buildings at three separate frequencies. The three frequencies used in the measurement were: 900 MHz, 11.4 GHz, and 28.8 GHz. The three types of buildings used for the experiment were: the ITS Wing 4 of the Department of Commerce Radio Building in Boulder, CO, (concrete construction with steel reinforcement), a private residence (wood-frame house with brick veneer), and the storeroom between Wings 3 and 5 of the Radio Building (a building with metal siding).

2. DESCRIPTION OF THE EXPERIMENT

This section describes the instrumentation, calibration, and measurement sites used for the penetration measurements.

2.1 Instrumentation And Calibration

The measurement system included three transmitters mounted on a cart that could be moved inside buildings, and the ITS millimeter-wave van located outside the building for reception of the signals. The van is shown in Figure 1 and the transmitter cart is shown in Figure 2. The transmitter cart consisted of three separate calibrated signal generators connected to three separate antennas. The antennas on the cart were omnidirectional in the azimuthal plane to simulate the radiation coverage typical of the small antenna that would be used for a PCS handheld unit. The receiving antennas on the van consisted of two medium-gain horn antennas with 17 dBi at 11.4 GHz and 16 dBi at 28.8 GHz both with vertical polarization, and a vertically-polarized omnidirectional antenna at 900 MHz. The beamwidths in azimuth and elevation of the 11.4-GHz horn were both 22 degrees, and the beamwidths for the 28.8-GHz horn were both 25 degrees. The horn antennas provided adequate angular coverage for receiving most of the multipath signals radiated from the transmitters inside the buildings under test, but favored the direct path and multipath signals arriving within their beamwidths.

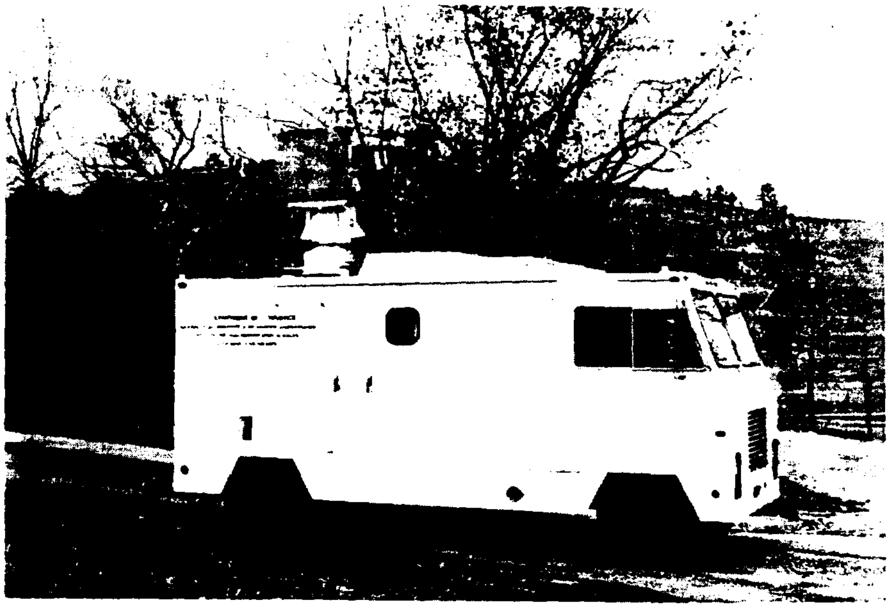

Figure 1. ITS millimeter-wave measurement van (receiver).

Figure 2. Remote source cart (transmitter).

This was not the case for the omnidirectional antennas. The omnidirectional antenna used at 900 MHz provided near equal response to the direct signal and all multipath signals arriving at the receiver, and therefore the destructive interference phenomenon was more likely to produce signal cancellation with deeper nulls than that attained at the higher frequencies with the horn antennas. The omnidirectional antenna vectorially adds all of the multipath return signals from all directions.

The outputs from the receiver antennas at 11.4 and 28.8 GHz were first converted down in frequency and then passed through separate logarithmic amplifiers. The output of each of the logarithmic amplifiers was a DC voltage proportional to the logarithm of the RF input power. This DC voltage was then sampled using an analog-to-digital (A/D) converter and the samples were stored in data files by a data acquisition program on the computer. The noise figure of the receiver system for the 11.4- and 28.8-GHz measurement was approximately 7 dB.

The output signal from the 900-MHz receiver antenna was applied directly to the spectrum analyzer input. The amplitude of the signal at 900-MHz was measured by the spectrum analyzer and sent to the data logging computer via the IEEE 488 BUS. The spectrum analyzer had a noise figure of approximately 20 dB at 900 MHz.

The system was calibrated to power levels relative to free space for each of the three frequency bands at a distance of 25.6 m over a grass-covered field at the end of Wing 4 of the Radio Building.

The measured free-space signal level at 25.6 m was used to normalize the signal level at each data point during the data processing to determine the actual free-space signal level at each distance. The free-space signal level was determined by averaging the signal received over a 2-min data collection interval at the 25.6-m receiver-to-transmitter distance. This free-space signal level was corrected for the actual distance and then subtracted from the measured signal level at each data point to determine the penetration loss for a signal propagating between the interior and the exterior of the building.

The received signal for all configurations consists of a direct wave and at least one wave reflected from the ground or some other obstruction. The vector addition of the direct and single or multiple reflected waves results in both constructive and destructive interference as a function of receiver-to-transmitter distance, antenna heights, and the radio frequency. The geometry for all sets of data provided a measurement of the excess attenuation experienced by the electromagnetic waves passing through the building structures for any situation that would be encountered for personal communications.

The signals at all three frequencies were sampled at sufficent intervals (1 sample/s) to characterize the data even though they were not sampled every half wavelength at the two upper frequencies (11.4 and 28.8 GHz). The linear distance between nulls and peaks for the sampled waveform created by constructive and destructive interference does not repeat every half wavelength. It is a function of the signal frequency, distance between the transmitter and receiver, transmitter antenna height, and receiver antenna height. If the receiver or transmitter moves horizontally, as was the case in the measurements performed here, the distance between two consecutive minima or maxima is given by

$$D = LR^2/2H_1H_2,$$

where D is the distance between two successive minima or maxima in meters, L is the wavelength in meters, R is the distance between the receiver and the transmitter in meters, H_1 is the transmitter antenna height in meters, and H_2 is the receiver antenna height in meters.

This distance was calculated for each of the three frequencies using the parameters that would result in the smallest distance between minima or maxima. The shortest distance R used during the measurements was 15 m. The transmitter height H_1 was 1 m. The receiver height H_2 was 3 m. The resulting distances D between minima or maxima for 900 MHz, 11.4 GHz, and 28.8 GHz were 12.50, 0.99, and 0.40 m, respectively. Referring to any of the Figures in the Appendix (A-1 through A-58), the data were sampled at least every 0.2 m, so there are at least two samples for each periodic variation of the signal as the transmitter cart was moved along all of the measurement paths. The formula above is for the periodicity of the minima and maxima variation for only the direct and reflected waves. Waves from higher order multipath signals would tend to fill in these nulls, so the case considered here is the worst-case multipath condition. The sampling of the data is therefore adequate to describe the signal fluctuation and hence compute the building attenuation.

2.2 Measurement Sites

Radio Building:

The Department of Commerce Radio Building in Boulder, CO is a concrete structure with steel reinforcement throughout. Wing 4 of the Radio Building is shown in Figure 3, with the ITS measurement van located at the end for the first sequence of measurements. There is a large amount of metal within the building for electrical conduit and structural support. The external walls of the building are concrete with re-bar reinforcement. The interior walls are mostly of cinder block with additional partitions with wood studs and gypsum dry wall. The metal-frame windows in each of the